# Current-Induced Switching in a Single Exchange-Biased Ferromagnetic Layer

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Abstract

We demonstrate current-induced switching effects in a single exchanged-biased ferromagnetic layer. A nanodomain can be switched within the ferromagnetic layer by a spin polarized current injected through a point contact. The high resistance of the hysteretic switching is due to formation of a domain wall between the nanodomain and the rest of the layer. The switching behavior observed in a single layer is a new type of spin-transfer torque effect which is the inverse effect of domain wall magnetoresistance. At room temperature, non-hysteretic switching behavior with a broad switching current density range is observed.

Recently, much attention has been focused on the current-induced switching (CIS) effect[1-8], with which the magnetic configuration of two magnetic entities can be switched by a spin polarized current rather than a magnetic field. This is because a sin polarized current carries spin angular momentum. A part of this angular momentum can be transferred to a magnetic entity as a torque, via the spin-transfer torque (STT) effect[9-12]. A common geometry for realizing the CIS effect is an FM/NM/FM trilayer, where the two ferromagnetic (FM) layers are physically separated by a nonmagnetic (NM) layer. The thicker FM layer works as the "fixed" layer, while the thinner FM layer is the "free" layer. The torque induced by a current with sufficient current density flowing perpendicularly through the trilayer can align the "free" layer parallel and anti-parallel to the "fixed" layer, depending on the polarity of the current. The switching of the configuration of the two magnetic layers can be verified via its inverse effect, the giant magnetoresistance (GMR) effect.

This work demonstrates CIS effects in a *single* exchange-biased FM layer. A magnetic nanodomain in a magnetic layer can be manipulated to be parallel and anti-parallel to the rest of the film by a current injected through a point-contact. The parallel configuration with low resistance and anti-parallel configuration with high resistance are confirmed by the magnetoresistance (MR) of the contact at a current close to zero. The absolute magnitude of the resistance change observed in the single layer is larger than those observed using trilayers. At room temperature, non-hysteretic switching with reduced switching current density is observed.

The schematics of our experimental setup are shown in FIG. 1(a). The 400 nm Co film was made by sputtering and a thin antiferromagnetic CoO layer was formed on the top by natural oxidation. The CoO layer on one surface of the Co layer causes the two Co surfaces to be different. The sample was field-cooled in a vacuum jacket from room temperature down to 4.2K with an in-plane magnetic field $H = +5$ T, then the field was ramped to zero. The sign of the initial magnetic field established the preferential alignment of the top Co surface towards the $+H$ direction through the exchange-bias mechanism. A point contact, which accommodated the necessary high current density for CIS effect, was then made on the surface of the top by approaching a Cu tip to the layer using a differential screw mechanism. Resistance ($V/I$) and differential resistance ($dV/dI$) as a function of current ($I$) were separately measured at the same time using the lock-in technique. The polarity of the current is positive when the current is flowing from the tip to the thin film.

Hysteretic switching loops were observed in both resistance and differential resistance versus current curves at $T = 4.2$ K as shown in FIG. 1(b), (c), and (d), similar to those obtained in Co/Cu/Co trilayers using point-contact spin injection[8] and nanopillars[1-7]. As described below, this switching is due to the magnetization reversal of a nanodomain underneath the contact and above the rest of the film. The switching currents are different for different contact resistances (FIG. 1(b), (c) and (d)). However, they all share a common switching current density which is - $(4.8\pm0.6)\times10^9$ A/cm$^2$ for negative side and + $(4.5\pm1.3)\times10^9$ A/cm$^2$ for positive side as shown in FIG. 1(e) using a ballistic model[13].

The high and the low resistances of the switching indicate that there are non-collinear magnetizations in the vicinity of the contact. This was further confirmed by the MR measurement with an in-plane magnetic field using a small current of 0.1 mA, which causes no STT effect. As shown in FIG. 2(a), the resistances of parallel and anti-parallel states are the same for both CIS effect and MR results. Similar to that in trilayers, the nanodomain works as the "free" layer while the rest of the film works as the "fixed" layer. The torque exerted on the nanodomain when a current is injected through the point contact can align the magnetization of the nanodomain parallel and anti-parallel to that of the rest of the film depending on the polarity of the current, while the magnetization of the rest of the film remains intact. For MR measurement in a low field range (±0.4 T, FIG. 2(a)), the nanodomain is exchange-biased and remained in positive orientation, only the magnetization of the rest of the film switches at ±31.5 mT. In the high field range (±0.8 T, FIG. 2(b)), the nanodomain switches when the exchange bias is overcome by the applied field. As shown in FIG. 2(b), the exchange-biased nanodomain switches asymmetrically at -695 mT and +72 mT while the rest of the film switches symmetrically at ±31.5 mT.

Several crucial aspects should be emphasized. First of all, in trilayers where two magnetic layers are physically separated by a non-magnetic layer such as Co/Cu/Co, the CIS effect is the inverse effect of the GMR effect. Here in a single exchange-biased layer, there is no GMR effect. The CIS effect is the inverse effect of domain wall magnetoresistance (DMR). Secondly, the switching current density as shown in FIG. 1(e) is about $4\times10^{9}$A/cm$^{2}$, which is about one order of magnitude larger than that of trilayers using point-contact spin injection[8] and nanopillars[1-7]. Thirdly, one notes the large resistance change of switching. One critical factor in the applications using CIS effect is the read-out signal[14]. If the resistance change is small, in the range of a few mΩ to 100 mΩ[1-8], one needs to resort to a lock-in technique to detect the small signal. A much larger change in resistance has been observed here in a single layer as shown in FIG.1 (b), (c) and (d). Even after normalization of the contact resistance, the resistance change is about one order of magnitude larger than those in trilayers[8]. Although we cannot determine a percentage value of the DMR because of the dominance of the contact resistance, the larger absolute DMR value observed in the single layer compared to the absolute GMR obtained in trilayers with similar contact resistances suggests that DMR is likely to be larger than GMR.

We observed the same resistance change independent of whether the domain results from the application of an applied field or a current. This similarity rules out artifacts caused by the forces on magnetic objects in an applied field. Artifacts due to magnetostriction are also likely to be small because the size of the nanodomain is so small. Magnetostrictive effects are important in macroscopic samples, where a very small relative change in a macroscopic length can be important on atomic length scales.

We have also observed non-hysteretic switching at room temperature for the same sample as shown in FIG. 3. It is non-hysteretic without sharp resistance step because at room temperature, which is higher than the blocking temperature of the antiferromagnetic layer, the domain wall can not exist at zero current without the assistance from exchange bias. In FIG. 3, the STT behavior starts almost from zero current and saturates at $j_S$ = $2.35\times10^9$A/cm$^2$, which is about half of the switching current density at 4.2 K. The resistance starts to increase from 49.32 Ω at a small current, and reaches 51.02 Ω at $j_S$ where full anti-parallel state attains with a resistance change of about 1.5 Ω as shown in FIG. 3. In between the low and high resistance, the resistance changes continuously and reversibly. This behavior could be due to a progression of magnetic states through large angle precessional states[15-17], thermal activation[18] between two metastable states, or possibly the continuous evolution of some static state.

In summary, current-induced hysteretic switching effect has been demonstrated in a single exchange-biased Co layer. This is a new type of spin-transfer torque effects revealed as the inverse effect of domain wall magnetoresistance. The switching current density and the change of resistance are both about one order of magnitude larger than those in trilayers. At room temperature, non-hysteretic behavior with a broad switching current density range has been observed.

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References:


1. E. B. Myers *et al.*, Science **285**, 867 (1999).

2. J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999).

3. J.-E. Wegrowe *et al*. Europhys. Lett. **45**, 626 (1999).

4. J. A. Katine *et al.*, Phys. Rev. Lett. **84**, 3149 (2000).

5. F. J. Albert *et al.*, Phys. Rev. Lett. **89**, 226802 (2002).

6. S. Urazhdin *et al.*, Phys. Rev. Lett. 91, 146803 (2003)

7. B. Özyilmaz *et al.*, Phys. Rev. Lett. **91**, 067203 (2003).

8. T. Y. Chen, Y. Ji and C. L. Chien, Appl. Phys. Lett. **84**, 380 (2004).

9. L. Berger, Phys. Rev. B **54**, 9353 (1996).

10. J. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).

11. Ya. B. Bazaliy, B. A. Jones, and S. -C. Zhang, Phys. Rev. B **57**, R3213 (1998).

12. M. Tsoi *et al*., Phys. Rev. Lett. **80**, 4281 (1998).

13. Yu. V. Sharvin, JETP, (U.S.S.R.) 48, 984-985(1965)[Sov. Phys.-JETP 21, 655 (1965)].

14. J. Sun, Nature **425**, 359 (2003).

15. M. Tsoi *et al.*, Nature **406**, 46 (2000).

16. S. I. Kiselev *et al*., Nature **425**, 380 (2003).

17. W. H. Rippard *et al.*, **92**, 027201 (2004).

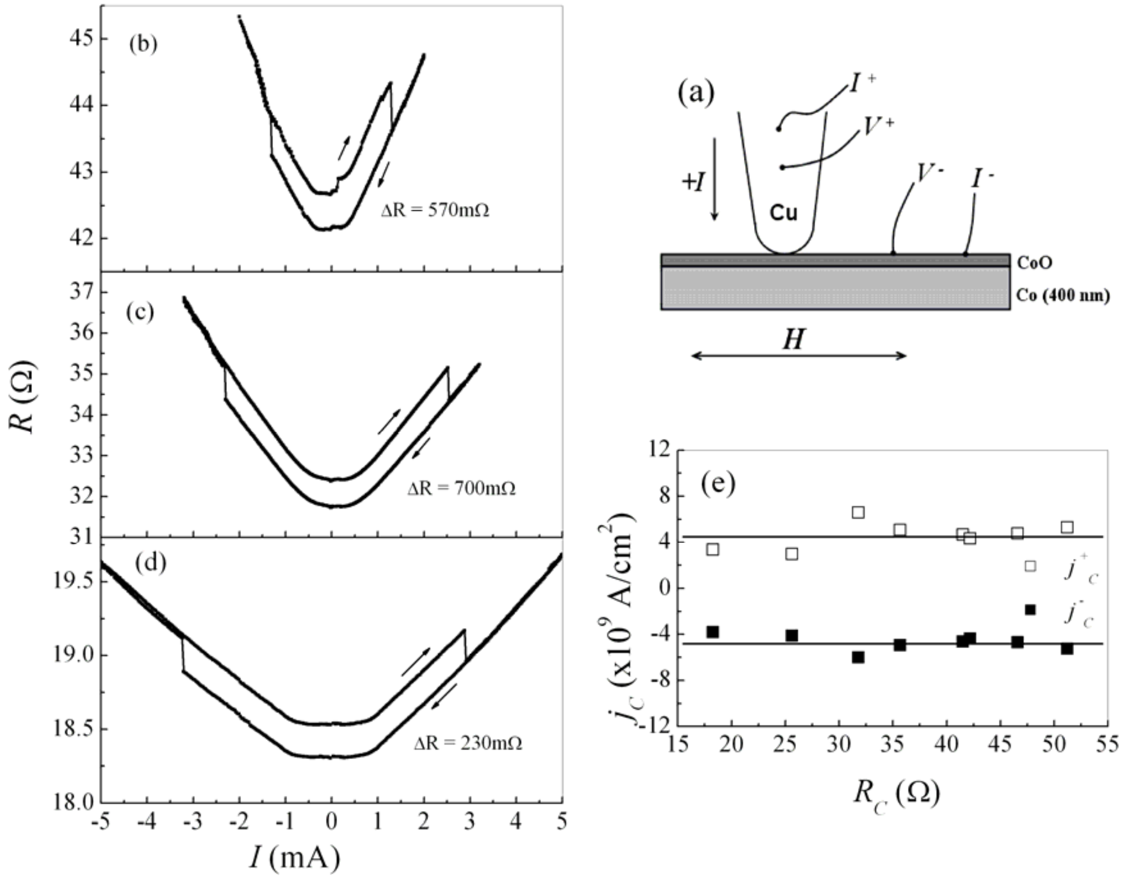
18. I.N. Krivorotov *et al*., cond-mat/0404003.

Figure Caption Page:

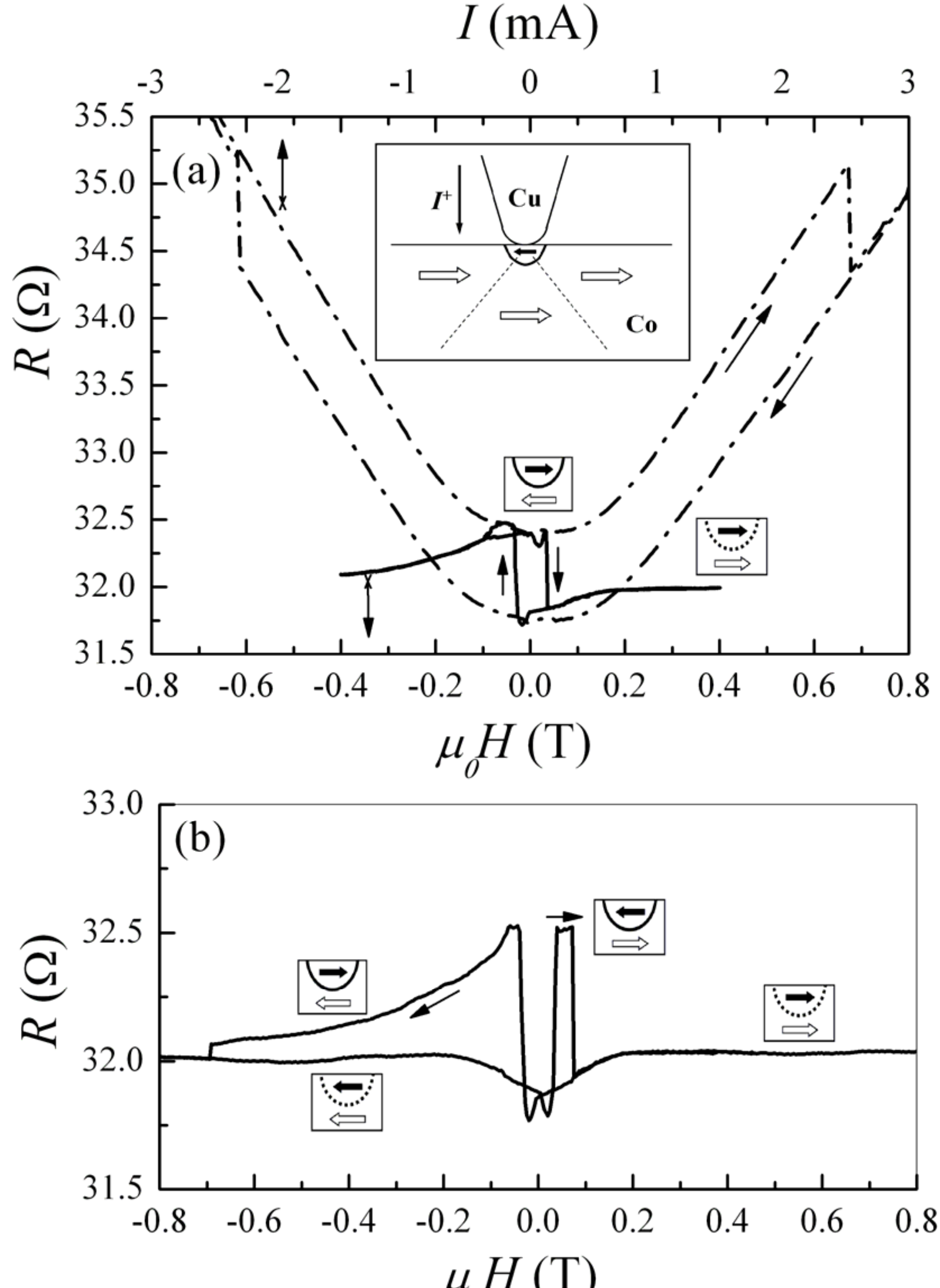
FIG. 1. (a) Schematics of experimental setup; (b), (c) and (d) Representative current-induced switching loops; (e) Switching current density for different contacts.

FIG. 2. (a) Current-induced switching loop as a function of current (dashed line) and magnetoresistance as a function of field at a low bias current of 0.1 mA in the low field range ±0.4 T and (b) high field range of ±0.8 T.

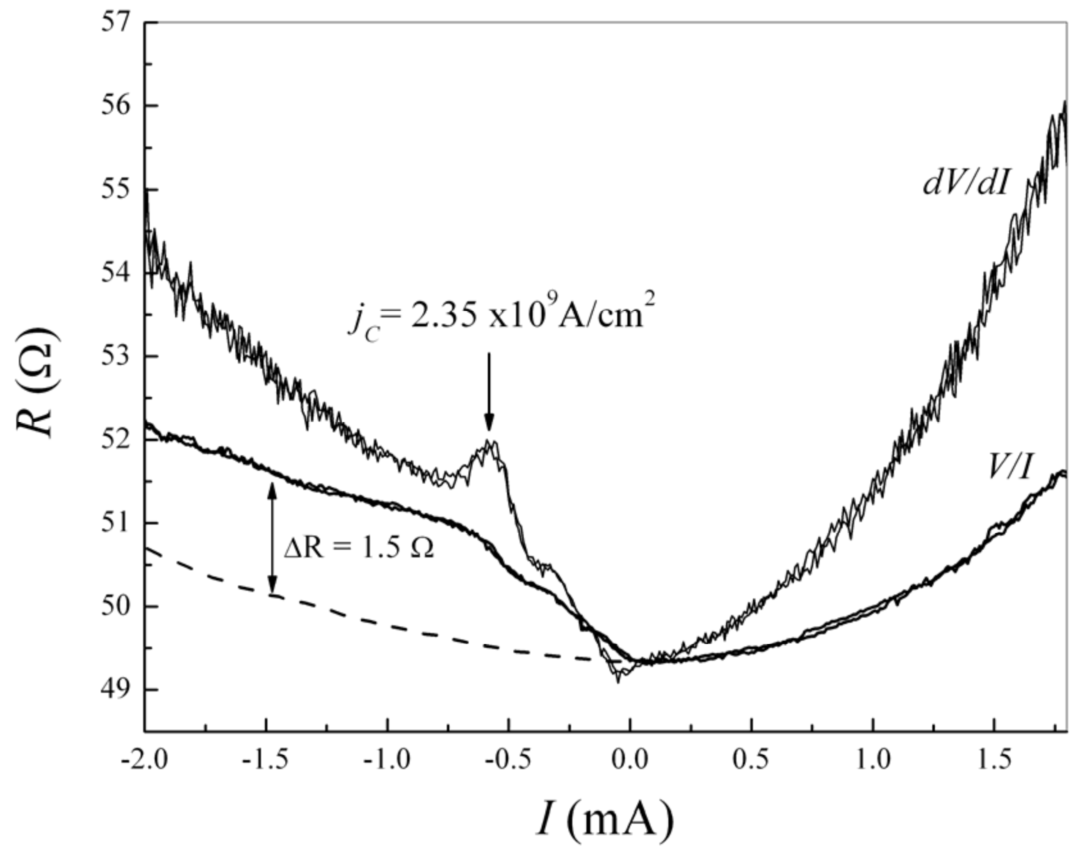
FIG. 3 Spin-transfer torque effect at room temperature (Dashed line is the mirror of positive side assuming no STT effect).



(a)
$I^+$
$V^+$
$V^-$
$I^-$
+I
Cu
CoO
Co (400 nm)
H
(b)
ΔR = 570mΩ
(c)
ΔR = 700mΩ
(d)
ΔR = 230mΩ
R (Ω)
I (mA)
(e)
$j^+_C$
$j^-_C$
$j_C$ (x10$^9$ A/cm$^2$)
$R_C$ (Ω)



I (mA)
-3
-2
-1
0
1
2
3
35.5
35.0
34.5
34.0
33.5
33.0
32.5
32.0
31.5
R (Ω)
(a)
I+
Cu
Co
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
μ0H (T)
33.0
32.5
32.0
31.5
R (Ω)
(b)
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
μ0H (T)



57
56
55
54
53
52
51
50
49
R (Ω)
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
I (mA)
dV/dI
V/I
j_C = 2.35 x10^9 A/cm^2
ΔR = 1.5 Ω